# COMPARISON OF ROCKWELL B HARDNESS (HRB) TESTS USING STEEL AND TUNGSTEN CARBIDE BALL INDENTERS

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**ABSTRACT:** Significant measurement differences occur in Rockwell B hardness (HRB) tests when using 1.588 mm diameter ball indenters made of steel and tungsten carbide (WC). In this paper, finite element analysis (FEA) is used to simulate the HRB indentation process using steel, tungsten carbide and rigid ball indenters on the same tested materials under the same testing conditions. The influence of the deformable indenters (made of steel and WC) on the HRB indentation is assessed by comparing their FEA results with those of a non-deformable rigid indenter. The deformations of both the indenters and tested materials during the loading and unloading period are analyzed. The effect of deformable ball indenters on HRB hardness measurement values is discussed and further verified by experiments.

**KEYWORDS:** Rockwell hardness, HRB, ball indenter, finite element analysis, FEA.

## 1. INTRODUCTION

The Rockwell B hardness (HRB)[1] test is a valuable and widely used empirical mechanical test method for evaluating mechanical properties of metallic materials. In the HRB test, a 1.588 mm diameter ball indenter is forced into the surface of the material under a single test at two specified levels of force (98.07 N and 980.7 N) using specific loading rates and dwell times. The HRB value is calculated based on the difference in the depth of the indentation at two specific times corresponding to the 98.07 N at the loading and unloading periods. The HRB tests are specified in the international standards of both the American Society of Testing and Materials (ASTM) and the International Organization for Standardization (ISO). In older versions of both the ASTM and ISO standards, only steel ball indenters were allowed for HRB tests. The tendency of steel ball indenters to flatten with use may result in erroneously elevated HRB values. For that reason, the revised standards ASTM E18-02 [1] and ISO 6508-1999 [2] allow the use of tungsten carbide (WC) ball indenters. From the HRB tests performed at the National Institute of Standards and Technology (NIST) [3] and at industrial testing laboratories, it was found that there are significant differences in the HRB results when using ball indenters made of steel and tungsten carbide for the same test material and testing conditions. It is important to study the effect of different indenter materials on the HRB tests. In this paper, finite element analysis (FEA) is used to simulate the HRB indentation process using steel, tungsten carbide and rigid ball indenters. The FEA model is described in section 2. In section 3, the influence of the deformable indenters (made of steel and WC) on the HRB indentation is assessed by comparing their FEA simulation results with those of a non-deformable rigid indenter. The deformation of the indenters and tested materials in the elastic and plastic regime during both the loading and unloading period are analyzed. The effect of deformable ball indenters on the HRB hardness measurement value is discussed and compared with the experimental results.

## 2. THE FEA MODEL FOR HRB MEASUREMENT SIMULATION

Commercial FEA software was used to model and simulate the HRB indentation process. With the advantage of axisymmetry of both the ball indenter and the test specimen,

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[1] International test methods [1, 2] require an ‘S” or ‘W” to be added to the HRB designation when steel or tungsten carbide ball indenters are used, respectively. For this paper, when only the HRB designation is given, it indicates the general Rockwell B hardness procedure, regardless of the type of indenter that is used.

**Table 1 Mechanical properties of the indenters**

| Indenter | Young's Modulus $E$ (GPa) | Poisson's ratio $\upsilon$ |
|---|---|---|
| Steel | 203.4 | 0.3 |
| WC | 633 | 0.22 |
| Rigid | $\infty$ | N/A |

only one radial-axial plane was modeled, significantly reducing the complexity of the simulation, and greatly improving the simulation efficiency. The 1.588 mm diameter ball indenter was modeled for both deformable metals (steel and WC) and a non-deformable rigid body. The ball indenter was represented by a two-dimensional quadrant, initially tangential with the specimen at the center point. A set of FEA meshes was constructed with an arrangement of quadrilateral, four-node axisymmetric elements. To save computing time, the mesh becomes coarser with increasing distance from the initial contact point. To eliminate boundary effects, the specimen size was selected as 8.1 mm × 8.1 mm which was considered being sufficient for both the accuracy and efficiency of the FEA process.

The material properties of the steel and tungsten carbide ball indenters were obtained from a material database [4] as shown in Table 1. In the FEA simulation, four specimens of different materials and HRB hardness levels were selected. They are aluminum 2024T4 (78 HRBS), aluminum 6061T6 (58 HRBS), and two oxygen-free copper alloys (40 HRBS and 23 HRBS). The materials are modeled as a homogeneous elastoplastic time-independent material exhibiting strain hardening. The plastic deformation was modeled by the $J_2$ flow plasticity theory with isotropic hardening [5]. The friction coefficient between the specimen and the indenter was chosen as $f = 0.1$.

The boundary conditions include: restriction of the bottom of the specimen from moving downwards and restriction of the centerline of the specimen and deformable indenter from moving along the $r$-direction. For the rigid indenter, a concentrated force was applied at the reference point of the indenter, or the center of the ball indenter. For the deformable indenter, a rigid plate is added on the top of the quadrant cross section of ball indenter, and a concentrated force was applied at the reference point of the plate. Considering geometric nonlinearity with sliding contact interfaces, the full Newton-Raphson method was used for equilibrium iteration of the finite element equations [5].

## 3. RESULTS AND ANALYSIS

In the Rockwell B hardness test, a preliminary force of 98.07 N is initially applied to the indenter. After holding the preliminary force for a specified time period, the indentation depth is measured, *h(loading)*. An additional force is then applied to the indenter to achieve a total force of 980.7 N, which is held constant for a specified time. The additional force is then removed, returning to the 98.07 N force level. The indentation depth, *h(unloading)*, is then measured a second time. The HRB hardness value is based on the difference in the two depth measurements as

$$HRB = 130 - \frac{\Delta h\ (mm)}{0.002\ mm}, \tag{1}$$

where $\Delta h = h(unloading) - h(loading)$. (2)

Since all indenter material deforms under loading, the measurement of indentation depth $h$ [for both *h(loading)* and *h(unloading)*] includes both the depth, $h_{specimen}$, due to the deformation of the material being indented, as well as the depth, $h_{indenter}$, due to the deformation of the ball in the direction of the loading, as

$$h = h_{specimen} + h_{indenter}. \tag{3}$$

For the non-deformable rigid indenter, $h_{indenter}(rigid) = 0$. To study the effect of deformable indenters on the indentation depth, we calculate the difference between the indentation depth of a steel or WC ball as compared with the indentation depth that would occur with a rigid indenter, and refer to this difference as a relative indentation depth $\tilde{h}$ as,

$$\tilde{h} = h(deformable) - h(rigid) \tag{4}$$

where $h(rigid) = h_{specimen}(rigid) + h_{indenter}(rigid)$ (5)
is the indentation depth modeled for a rigid ball, and

$$h(deformable) = h_{specimen}(deformable) + h_{indenter}(deformable) \tag{6}$$

is the indentation depth modeled for a steel or WC ball. From Eq. 3 and 4 above, it follows

$$\tilde{h} = \tilde{h}_{specimen} + \tilde{h}_{indenter} \tag{7}$$

where $\tilde{h}_{specimen} = h_{specimen}(deformable) - h_{specimen}(rigid)$ is the relative indentation depth due to the material deformation using a steel or WC ball as compared with a rigid ball, $\tilde{h}_{indenter}$ is simply represented by $h_{indenter}(deformable)$, since $h_{indenter}(rigid) = 0$.

We can also calculate the difference in the relative indentation depth $\Delta\tilde{h}$ for both loading and unloading periods as

$$\Delta\tilde{h} = \Delta\tilde{h}_{specimen} + \Delta\tilde{h}_{indenter} \tag{8}$$

where $\Delta\tilde{h}_{specimen} = \tilde{h}_{specimen}(unloading) - \tilde{h}_{specimen}(loading)$

and $\Delta\tilde{h}_{indenter} = \tilde{h}_{indenter}(unloading) - \tilde{h}_{indenter}(loading)$.

Therefore, the relative $\Delta$HRB measurement values between a deformable steel or WC ball and a rigid non-deformable ball can be calculated from

$$\Delta HRB = \frac{\Delta\tilde{h}}{0.002\ mm}, \tag{9}$$

where $\Delta\tilde{h}$ is in mm.

### 3.1 Ball indenter deformation

From Eq. 3, it can be seen that the deformation of the indenter ball contributes to the HRB measurement value. The steel ball elastic strain distribution during the maximum loading is shown in Fig. 1. It can be seen that the elastic strain decreases from the bottom to the center. The ball tends to flatten elastically at the contact surface with the specimen during the indentation process. This flattening generates the ball deformation $h_{indenter}$.

Fig. 2 shows the steel and WC ball deformation vs. indentation force for the same test material and conditions. It can be seen that the ball deformation during the loading is larger than that of the unloading period at the same load. This is because of the plastic deformation of the test material during the indentation tests. The contact area during unloading is much larger than that during loading for the same force, which decreases the contact pressure, resulting in a decreased ball deformation. In addition, since the Young's modulus of steel is lower than that of WC, the deformation of the steel ball is significantly larger than that of the WC ball for the same load, as shown in Fig. 2.

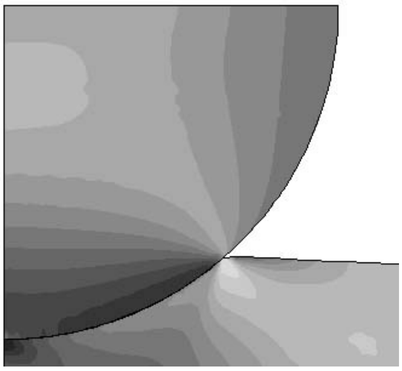


**Fig. 1 Steel ball max. elastic principal strain distribution at the maximum loading. The darker material region indicate higher strain.**

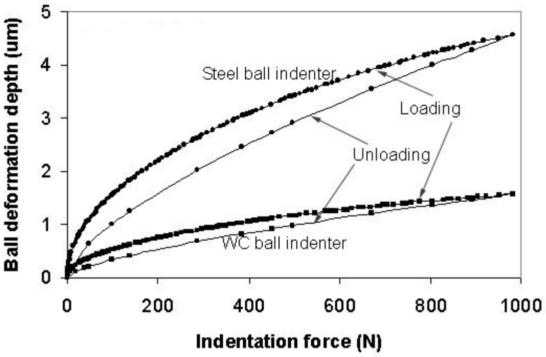


**Fig. 2 Steel and WC ball deformation vs. indentation force for the same test**

## 3.2 Comparison of HRB measurement values for steel and WC ball indenters

Based on the FEA simulation results, the indentation depth vs. time curves for steel and WC ball indenters are compared in Fig. 3. From Fig. 3, it can be seen that the indentation depth of the steel ball indenter is the highest during both the loading and unloading periods, followed by the WC indenter, and the indentation depth of the rigid indenter is the lowest. The relative indentation depth $\widetilde{h}$ between the deformable ball and the rigid ball during the loading period is much higher than during the unloading period. Therefore, the indentation depth difference $\Delta h$ of the steel ball is lower than that of the WC ball. From Eq. 1, the HRB result using a steel ball is higher than that when using a WC ball, and a rigid ball would have the lowest HRB value when testing the same material under the same test conditions.

## 3.3 Analysis of HRB differences using steel and WC ball indenters

In order to further analyze the HRB indentation process using steel and WC ball indenters, from Eq. 7 and 8, we separately study the effects of the indenter deformation and relative indented material deformation, as shown in Fig. 4.

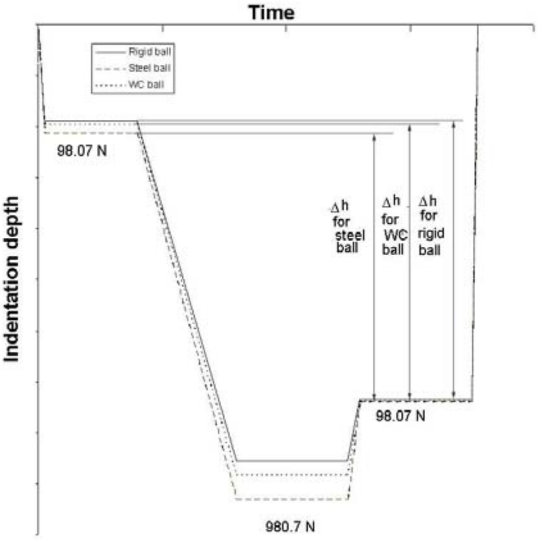
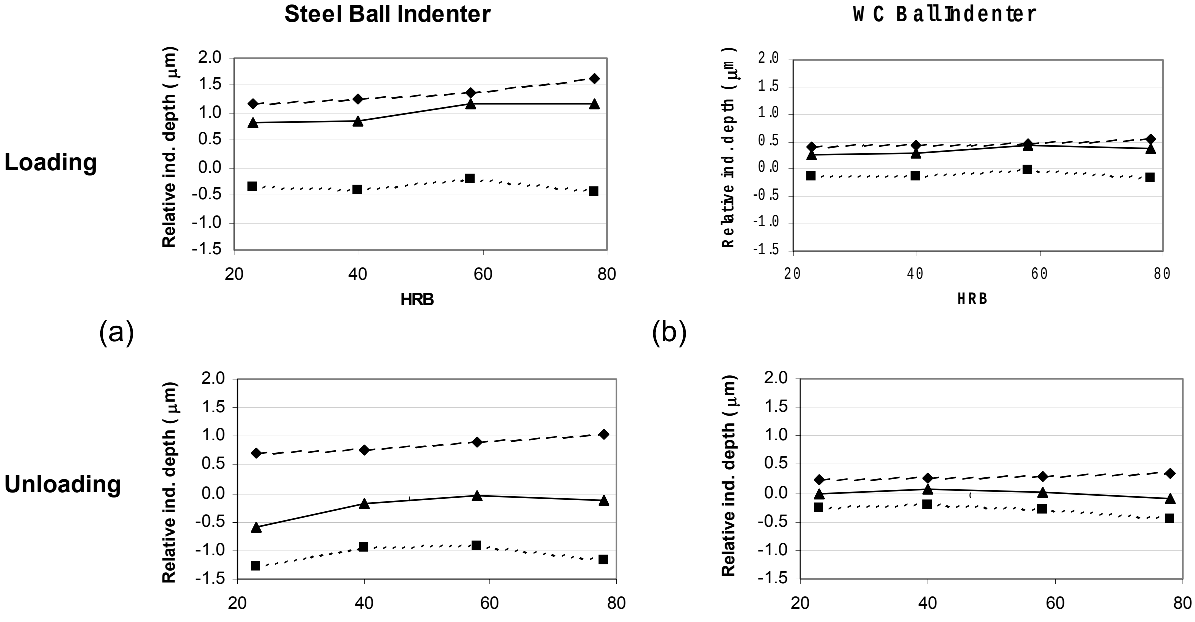


**Fig. 3 Indentation depth vs. time plot demonstrates the effect of different ball indenter materials.**



(a) (b) (c) (d)

**Fig. 4 The relation of indenter deformation $\tilde{h}_{indenter}$ (dashed line), relative specimen indentation depth $\tilde{h}_{specimen}$ (dotted line) and relative indentation depth $\tilde{h}$ (solid line) for steel (left column) and WC ball indenter (right column) during loading (a and b) and unloading (c and d) of the 98.07 N force at different HRB levels.**

It can be seen that the ball deforms more when testing harder materials (see dashed lines in Fig. 4). This is because the indenter-specimen contact area decreases for harder materials under the same indentation load. As a contrast, the relative specimen indentation depth $\tilde{h}_{specimen}$ is not simply an increasing or decreasing function (see dotted lines in Fig. 4), since the relative specimen indentation depth $\tilde{h}_{specimen}$ is determined by both contact pressure and material properties. For materials of increasing hardness, the contact area decreases causing an increase in the contact pressure for the same load, thereby increasing the relative specimen indentation depth $\tilde{h}_{specimen}$. At the same time, the increase of material hardness will decrease the relative specimen indentation depth $\tilde{h}_{specimen}$. The first effect has more influence on the high HRB materials while the second effect has a greater influence on the low HRB materials. The combined effect causes the deformation of the indented material to differ from a simple increasing or decreasing function of hardness level (see solid lines in Fig. 4).

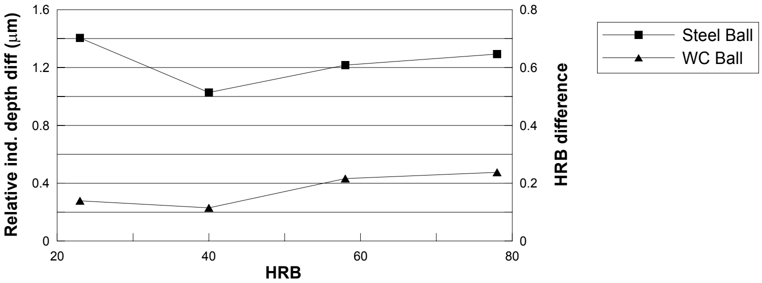


**Fig. 5 Relative indentation depth difference Ä$\tilde{h}$ and HRB difference between steel and WC balls.**

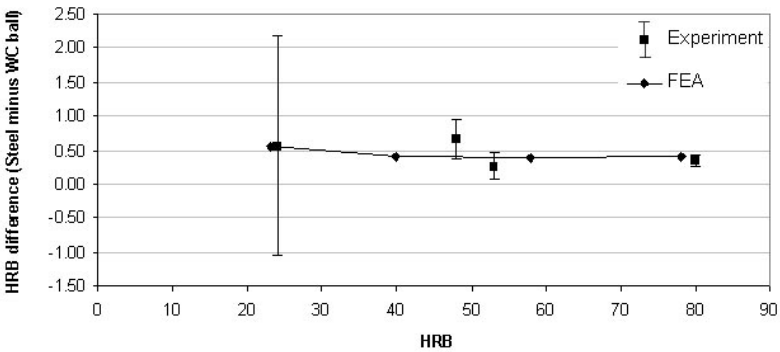


**Fig. 6 Comparison of HRB experiments and FEA prediction results using steel and WC ball indenters. The error bars represent one standard deviation of the mean difference from the two sets of measurement data of steel and WC indenters. The error bars reflect the non-uniformity in the test blocks.**

Fig. 5 shows the combined effect that the loading and unloading relative indentation depths $\tilde{h}$ have on the final relative indentation depth difference $\Delta\tilde{h}$, and the corresponding HRB values (see Eq. 9) for both steel and WC ball indenters. From Fig. 5, it can be seen that the final relative indentation depth difference $\Delta\tilde{h}$ between steel and WC ball is almost constant at three different high HRB levels, $\Delta\tilde{h} \cong 0.8$ μm, resulting in a 0.4 HRB difference. For the low 23 HRB level, this difference increases to 1.12 μm, or 0.56 HRB. This is in agreement with our experimental results, as shown in Fig. 6.

## 4. SUMMARY

In this paper, finite element analysis (FEA) is used to simulate the HRB measurements and analyze the effect of steel, WC and rigid ball indenters on the HRB measurement values. Because of a combined effect from both the ball deformation and indenter material deformation during the loading and unloading periods, the HRB difference between steel and WC ball indenters was found to be about 0.4 HRB for 40 to 78 HRB levels, but increased to 0.56 HRB at 23 HRB level. This agrees with our experimental results.

## ACKNOWLEGEMENT

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